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Collinear Twist-3 Approach to Transverse Single-Spin Asymmetry in Proton-Proton Collision

KOICHI KANAZAWA¹ AND ANDREAS METZ¹

*Department of Physics, SERC, Temple University, Philadelphia, Pennsylvania
19122, USA*

YUJI KOIKE²

Department of Physics, Niigata University, Ikarashi, Niigata 950-2181, JAPAN

DANIEL PITONYAK³

*RIKEN BNL Research Center, Brookhaven National Lab, Upton, New York 11973,
USA*

We present our recent analysis on the transverse single-spin asymmetry (SSA) in inclusive pion and direct-photon production in pp collisions for RHIC kinematics. The analysis includes the contributions from twist-3 quark-gluon-quark correlations in the proton and twist-3 fragmentation effects for the pion. Some of the functions appearing in the formula for the SSA, such as the soft-gluon-pole Qiu-Sterman function, the nucleon transversity, and the Collins function were fixed consistently with the SSA data in semi-inclusive DIS and in e^+e^- -annihilation, so that our analysis is free from the sign mismatch problem.

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1 Introduction

Clarification of the origin of transverse single-spin asymmetry (SSA) A_N has remained an important issue in high energy hadron physics since early measurements of A_N^π at E704 reported striking results that the asymmetries are up to 30% at forward rapidity [1, 2]. Subsequently, this novel spin phenomenon has also been observed at higher energies at RHIC [3, 4, 6, 7, 5, 8]. Since such large A_N cannot be explained within the collinear parton model [9], it requires an extension of the framework for QCD hard processes.

One such extension is the TMD factorization approach, which is applicable for low- P_T processes which contain a separate hard scale Q ($\gg P_T$) for a perturbative treatment. There, large A_N is attributed to the nonzero Sivers/Collins function which embodies the correlation between parton's intrinsic transverse momentum and hadron/quark spin. These functions have been extracted through phenomenological analyses of data in SIDIS and e^+e^- [10, 11, 12]. On the other hand, in high- P_T reactions, where P_T is regarded as a hard scale, large A_N can be described by means of twist-3 multiparton correlation effects in the framework of the collinear factorization. Of particular interest in the collinear twist-3 approach was the chiral-even soft-gluon-pole (SGP) function, also known as the Qiu-Sterman (QS) function. This effect was believed to be the main source of A_N^π for many years [13, 14, 15], and in fact the inclusion of this effect could lead to a reasonable description of RHIC data [16, 17, 18]. Recently, however, a challenging observation regarding consistency between the two approaches was made in Ref. [19], where it was argued that the QS function determined from pp data has an opposite sign to the one expected from SIDIS data. This infamous “sign-mismatch” problem cannot be resolved with a more flexible parameterization of the Sivers function pp [20], so that it has been recognized that the QS effect cannot be the main source of A_N^π in pp . Another evidence of this statement is the fact that within the collinear twist-3 approach one obtains the wrong sign for the neutron A_N in inclusive DIS when using the QS function extracted directly from A_N^π in pp [21]. Given these new progresses, it has become important to figure out what is the main cause of A_N^π as well as to test current knowledge on the QS function by getting additional information from the SSA in other processes.

In this report, we address these issues by looking into A_N^π and A_N^γ in pp . In the first part, we present our latest analysis of RHIC data on A_N^π . We demonstrate that the twist-3 fragmentation function can play a central role in the description of A_N^π and including this contribution leads to a unified description of the asymmetries in pp , SIDIS, and e^+e^- . In the latter part, we show our estimate of A_N^γ at RHIC kinematics based on the polarized cross section for the twist-3 quark-gluon correlation which recently we completed. Making a comparison with the one from the TMD approach, we argue that measurements of A_N^γ can help discriminate between these approaches. This report is a short summary of our recent papers [22, 23].

2 Fitting of A_N^π at RHIC

In principle A_N^π in pp receives contribution from both the twist-3 distribution and fragmentation functions. The former piece has been extensively studied in the literature [15, 16, 24] while the complete cross section formula for the latter has become available very recently [25, 26]. Interestingly, a phenomenological study with a simple model in Ref. [25] shows that the latter effect could be significant at RHIC kinematics. Here we perform a new fit of RHIC A_N^π data [3, 4, 5, 6] by including the whole contribution from the twist-3 fragmentation function and address whether this can resolve the sign-mismatch problem.

Let us begin with the setting for our fits. In order to evade the sign-mismatch problem on the QS function $T_F(x, x)$, we use the existing parameterization of the Siverts function f_{1T}^\perp which was extracted from SIDIS data. The rigorous relation between these functions reads [33]

$$T_F(x, x) = - \int d^2\vec{p}_\perp \frac{\vec{p}_\perp^2}{M} f_{1T}^\perp(x, \vec{p}_\perp^2) \Big|_{\text{SIDIS}}, \quad (1)$$

where the Siverts function is the one which shows up in SIDIS. In our analysis we try two different parametrizations in Ref. [10, 11]. Similarly, for the fragmentation contribution, we take advantage of the existing parameterization of the Collins function as well as take into account the relation between the relevant twist-3 functions in order to make our analysis consistent. First, we note the cross section formula for fragmentation contains three twist-3 fragmentation functions: H , \hat{H} , and $\hat{H}_{FU}^\mathfrak{S}$. Of these three, by invoking the EOM relation [26]

$$H(z) = -2z\hat{H}(z) + 2z^3 \int_z^\infty \frac{dz_1}{z_1^2} \frac{1}{\frac{1}{z} - \frac{1}{z_1}} \hat{H}_{FU}^\mathfrak{S}(z, z_1), \quad (2)$$

one can choose $\{\hat{H}, \hat{H}_{FU}^\mathfrak{S}\}$ as independent functions. In this way $H(z)$ is regarded an auxiliary function and is completely determined by the other two. The kinematical twist-3 fragmentation function $\hat{H}(z)$ can be fixed in terms of the TMD Collins function via the relation

$$\hat{H}(z) = z^2 \int d^2\vec{k}_\perp \frac{\vec{k}_\perp^2}{2M_h^2} H_1^\perp(z, z^2\vec{k}_\perp^2). \quad (3)$$

For the Collins function H_1^\perp , we take the parameterization from Ref. [12]. Concerning the 3-parton correlator $\hat{H}_{FU}^\mathfrak{S}$, so far no knowledge has been obtained as it has no counterpart in the TMD approach, and therefore this function needs to be determined by fitting pp data. We refer the reader to Ref. [22] for our parameterization as well as any other details of our fits.

Figure 1 shows the result of our fits. Overall, the pp data are successfully reproduced both for neutral and charged pions as a function of x_F , and we found most of

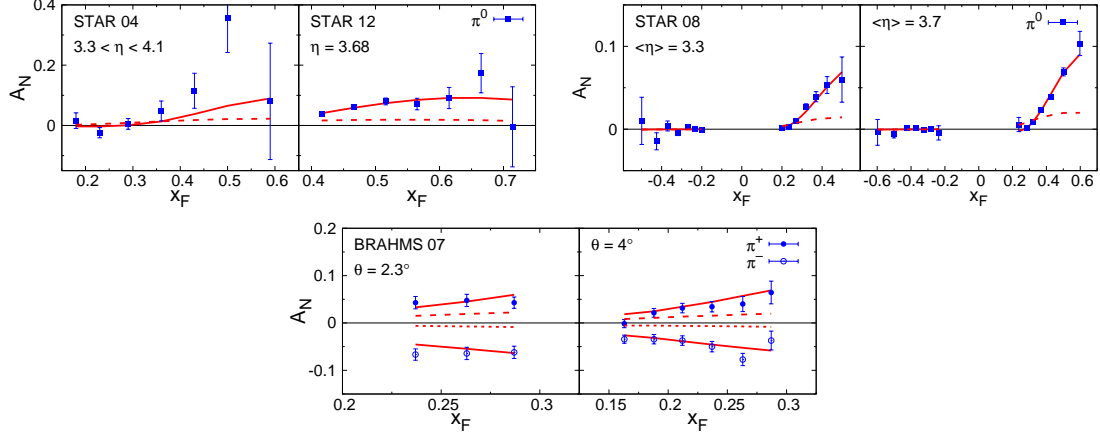


Figure 1: Fit result for pions. We included only the data at $\sqrt{S} = 200$ GeV from STAR and BRAHMS [3, 4, 5, 6]. The dashed curves are calculated without including \hat{H}_{FU}^S .

the contribution come from the twist-3 fragmentation function. Also, we plotted the dashed curves which show the calculation without including the contribution from the 3-parton correlator, namely it represents the contribution of \hat{H} . Obviously, this contribution is insufficient to reproduce the RHIC data and we found indeed the 3-parton correlator gives the dominant contribution and thus plays a crucial role in the description of the RHIC data.

In Fig. 2, we have presented our prediction for the P_T -dependence of A_N which is compared to the latest STAR data in [34]. One sees that the observed pattern is reproduced as well, supporting the validity of the collinear twist-3 approach.

3 Phenomenology of A_N^γ at RHIC

The SSA in direct-photon production in pp is a clean process to probe the twist-3 distributions inside proton because of the absence of fragmentation. By now the cross section for the quark-gluon and 3-gluon correlations in p^\uparrow is available in Ref. [13, 14, 29, 30, 31], where it was shown that the former effect to A_N^γ is much larger than the case of $A_N^{\pi^0}$ at forward rapidity while the latter becomes significant only at backward rapidity. In addition, in Ref. [23] we have derived the cross section for the chiral-odd quark-gluon correlation in p . With the complete formula in hand, here we give a new numerical estimate of forward A_N^γ at RHIC kinematics and see what we can learn from it.

The contribution from the quark-gluon correlation is classified into the ones from SGP and soft-fermion-pole (SFP), so in total there are four types of contributions:

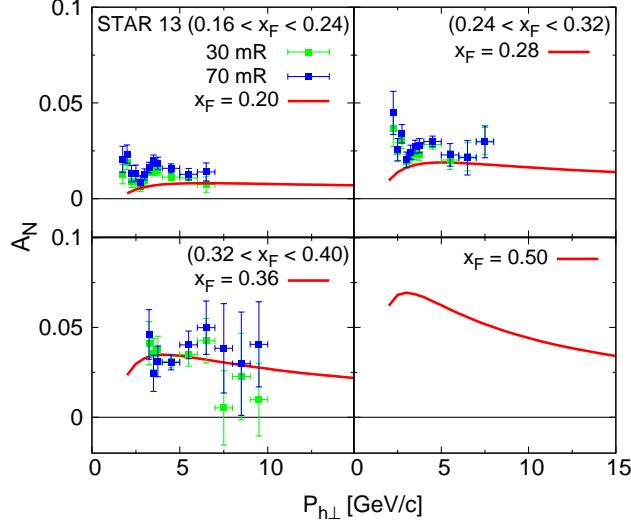


Figure 2: Comparison of P_T -dependence of A_N^π with the STAR data [34].

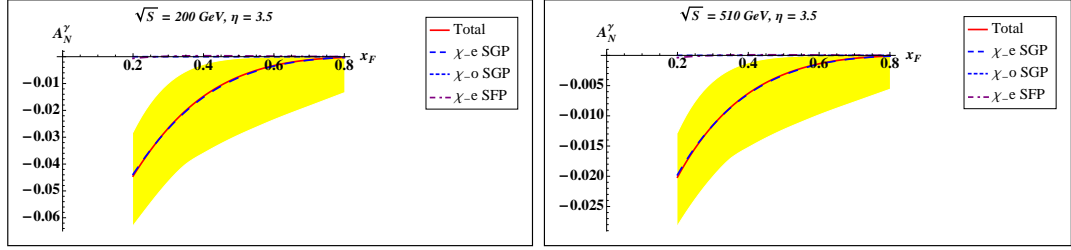


Figure 3: Estimate of A_N^γ at forward pseudorapidity $\eta = 3.5$ at two different energies.

(i) chiral-even SGP (QS effect), (ii) chiral-even SFP, (iii) chiral-odd SGP, and (iv) chiral-odd SFP. Of these four, in Ref. [23] we found there is no contribution from (iv) at leading-order QCD, so we focus on the other three. As in the case of A_N^π , we perform our calculation of A_N^γ consistently with the existing parametrizations of the relevant TMD functions. For this purpose, we again make use of Eq. (1) to fix the QS function. Likewise, we use another rigorous relation between the chiral-odd SGP function $E_F(x, x)$ and the Boer-Mulders function h_1^\perp [33]

$$E_F(x, x) = \pm \frac{1}{\pi M^2} \int d^2 \vec{p}_\perp \vec{p}_\perp^2 h_1^{\perp(\pm)}(x, \vec{p}_\perp), \quad (4)$$

where the sign $+$ ($-$) represents that the future-pointing (past-pointing) Wilson line is used in the definition of the Boer-Mulders function. For the Boer-Mulders function we take the parameterization from Ref. [32]. The only unknown input is the chiral-even

SFP function $T_F(0, x) + \tilde{T}_F(0, x)$. For this function, we make a simple assumption as

$$T_F(0, x) + \tilde{T}_F(0, x) = T_F(x, x), \quad (5)$$

to see its impact at the RHIC energy.

Figure 3 shows our estimates of forward A_N^γ at $\sqrt{S} = 200$ GeV and 510 GeV, respectively. We have found at both energies the asymmetry could be substantial and has negative sign. Also shown in the figure is the decomposition into the contributions from each function. Clearly, the asymmetry is dominated by the QS effect and the contribution from other sources are negligible, suggesting A_N^γ is an ideal observable to extract the QS function. Another interesting finding is that our result differs in sign from the prediction based on the TMD approach in Ref. [11]. This indicates ongoing and future measurements of A_N^γ are quite useful to discriminate between the two approaches.

4 Summary and outlook

We have presented our recent analyses on A_N^π and A_N^γ at RHIC kinematics. We have demonstrated the twist-3 fragmentation function can give the dominant contribution to A_N^π and including this effect leads to a good description of the RHIC data for neutral and charged pions. By construction, this analysis is consistent with the Sivers and Collins mechanisms in the TMD approach, and thus we have attained a first unified description of the asymmetries in pp , SIDIS and e^+e^- . In addition, we have provided a new prediction on A_N^γ based on the complete cross section for the twist-3 quark-gluon correlation. It turned out that the QS function is the only possible source to cause a substantial asymmetry in this process. Interestingly, our result differs in sign from the prediction based on the TMD approach. We expect ongoing and future measurements of A_N^γ will help discriminate the two approaches.

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